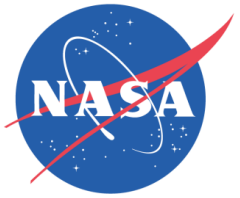
National Aeronautics and Space Administration



Development of Luminescence Lifetime-Based Surface Temperature Mapping for Environmental Barrier Coatings

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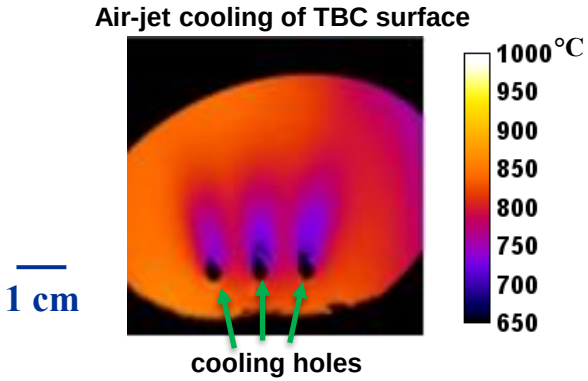
Objectives

- Develop luminescence lifetime imaging-based temperature mapping for EBCs featuring the same advantages observed for TBCs at lower temperatures.
  - \+ Well suited for evaluating steady state cooling strategies.
  - \+ Emissivity independent and no interference from reflected radiation.
  - – Limited to near steady-state conditions.

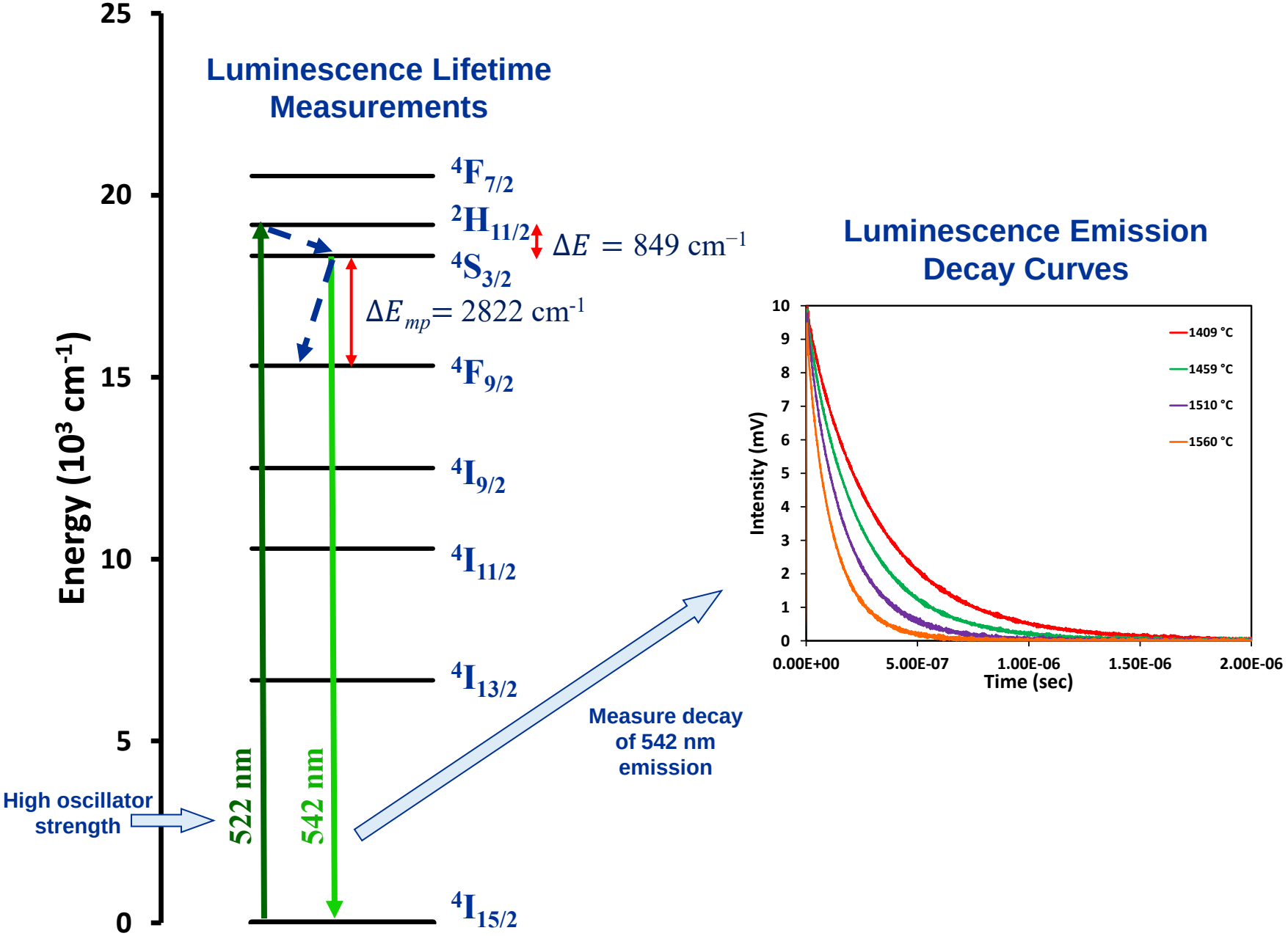


- Use EBC temperature mapping capability for evaluation of EBC performance and cooling strategies.

Approach

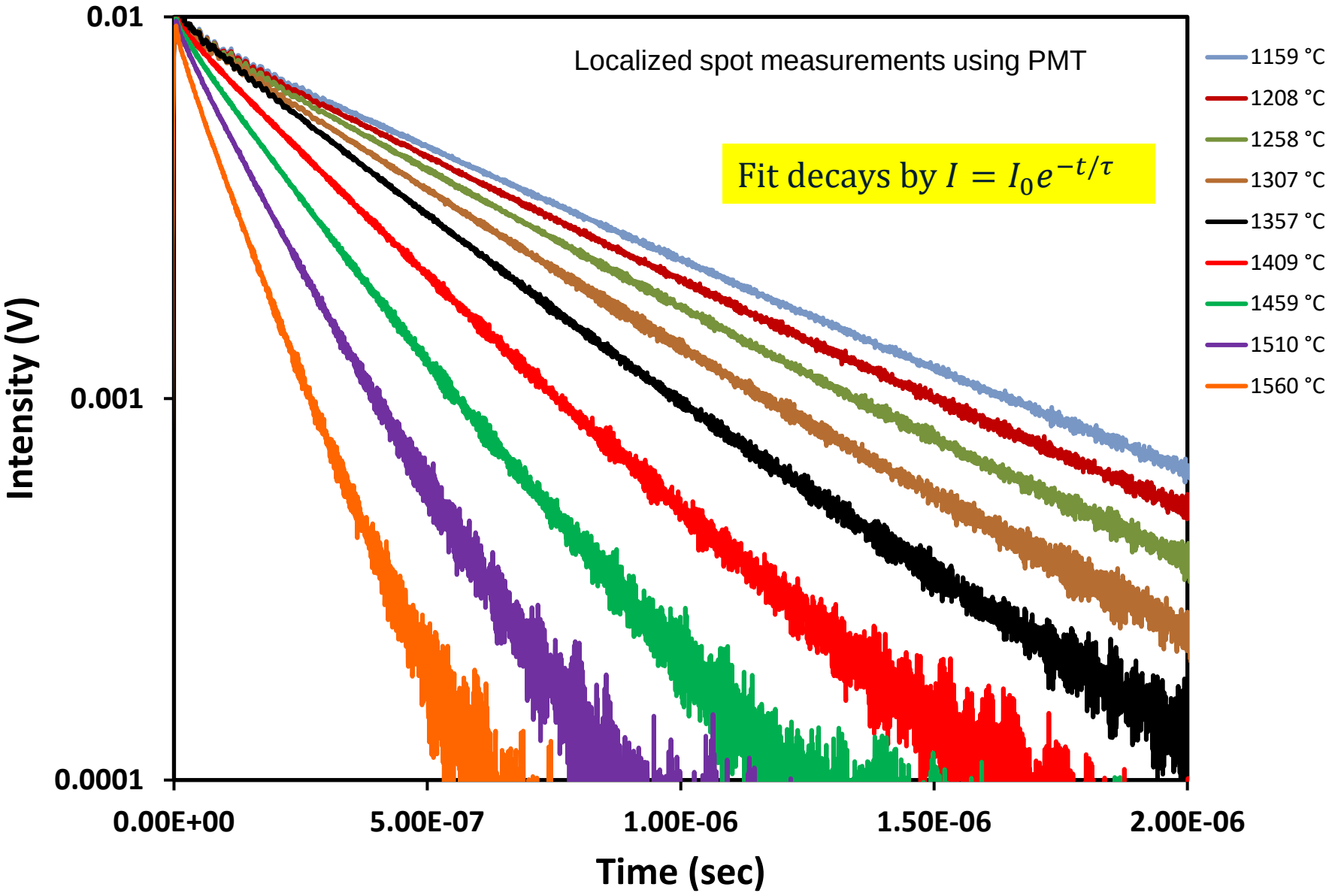
- Evaluate Y_2SiO_5:Er for luminescence lifetime-based temperature mapping to >1500 °C.
- Evaluate temperature mapping performance and the compatibility of Y_2SiO_5:Er temperature-sensing layer at the EBC surface.

Er^{3+} Electron Energy Level Transitions in Y_2SiO_5 Associated with Luminescence Lifetime Measurements

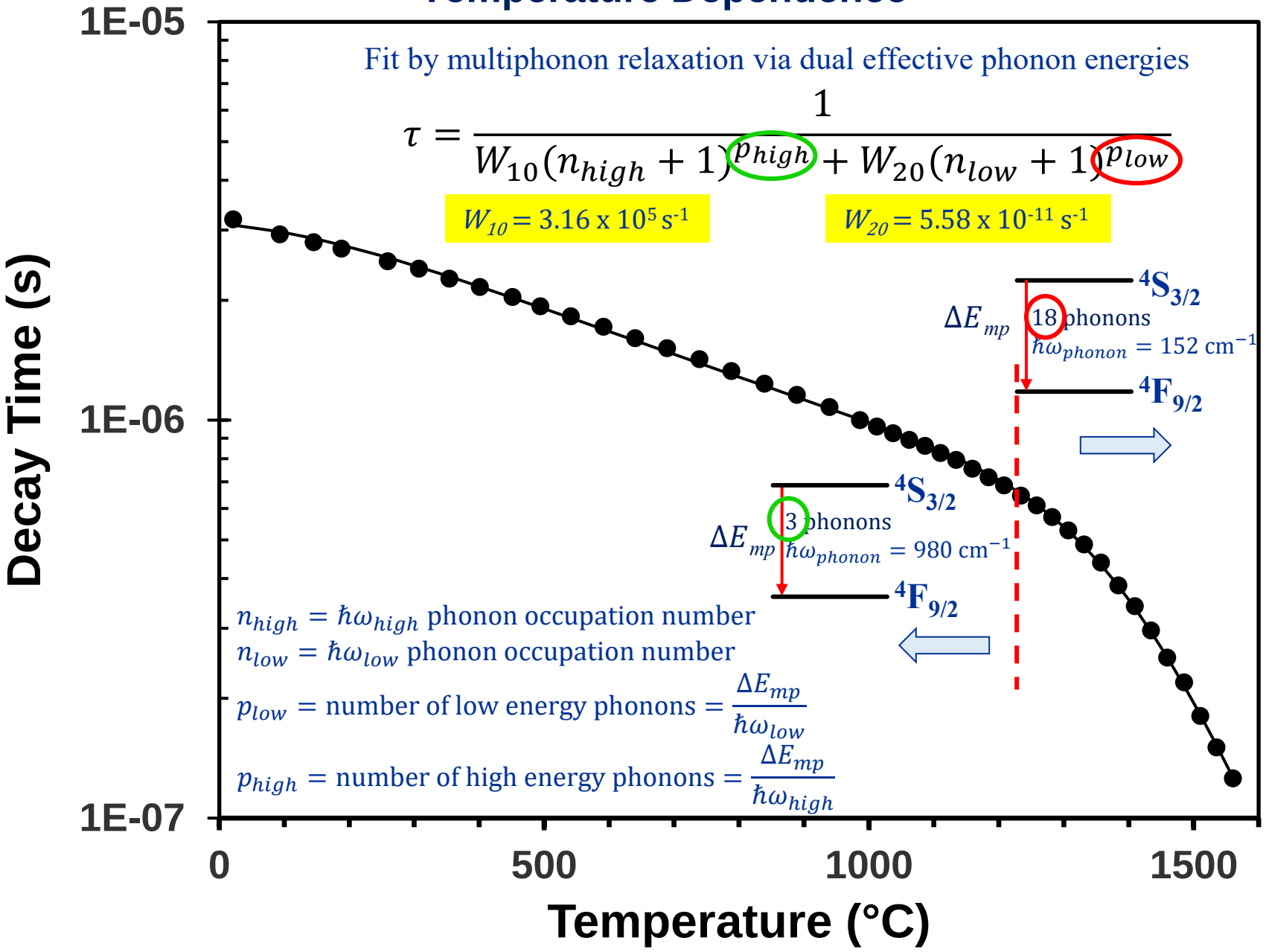


Y_2SiO_5:Er(0.8%) Emission Decay Curves

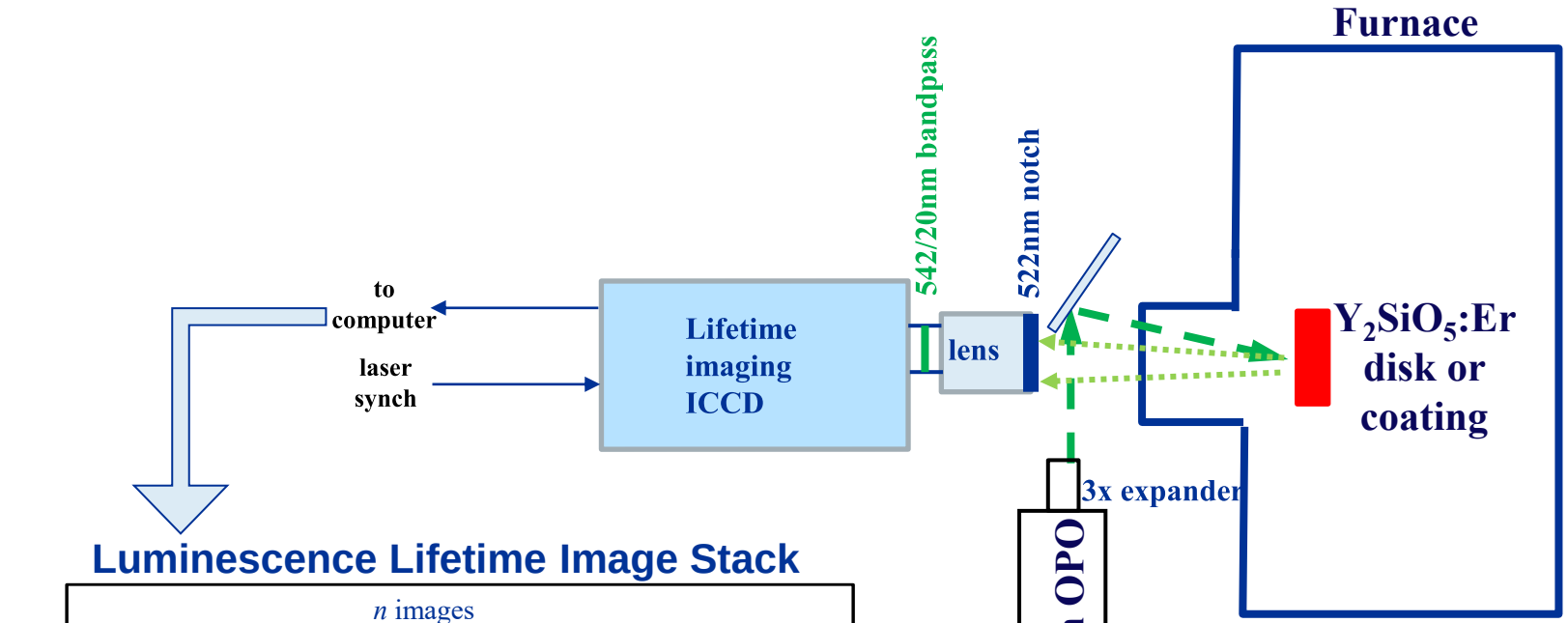
Temperature Dependence

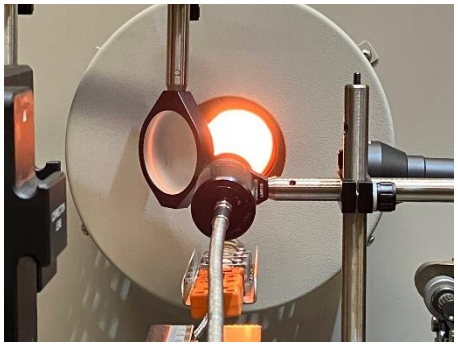


Y_2SiO_5:Er(0.8%) Decay Time
Temperature Dependence



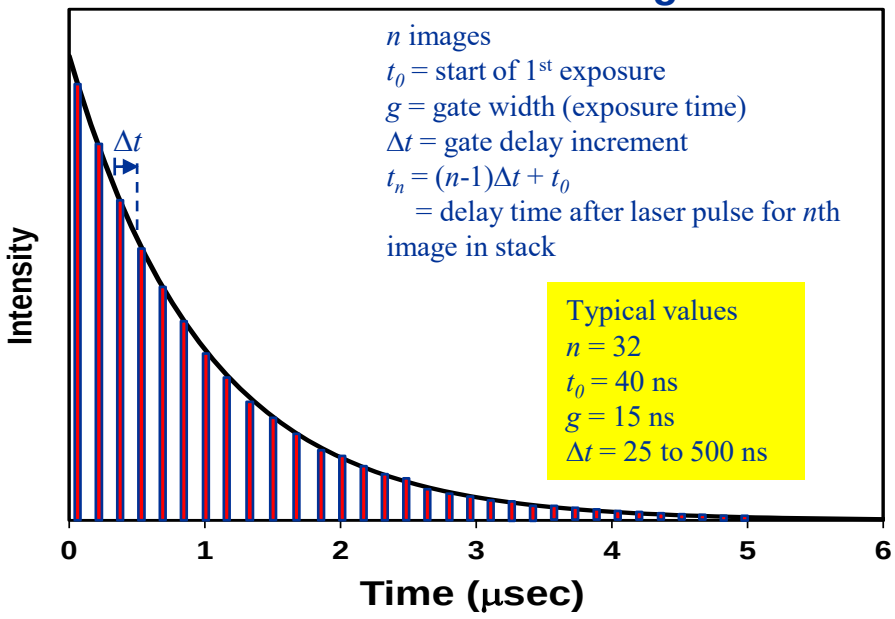
Luminescence Lifetime Imaging





Low background using small lens aperture (f/22) and short frame exposure (15 ns)

Luminescence Lifetime Image Stack



n images
t_0 = start of 1st exposure
g = gate width (exposure time)
Δt = gate delay increment
$t_n = (n\text{-}1)\Delta t + t_0$
= delay time after laser pulse for *n*th image in stack

Typical values
$n = 32$
$t_0 = 40$ ns
$g = 15$ ns
$\Delta t = 25$ to 500 ns

2D Temperature Maps from Luminescence Lifetime Imaging*

- Step 1: Acquire image stack of background-corrected exposures.
- Step 2: Fit single exponential decay to luminescence decay curve at ***each pixel*** to produce decay time map.

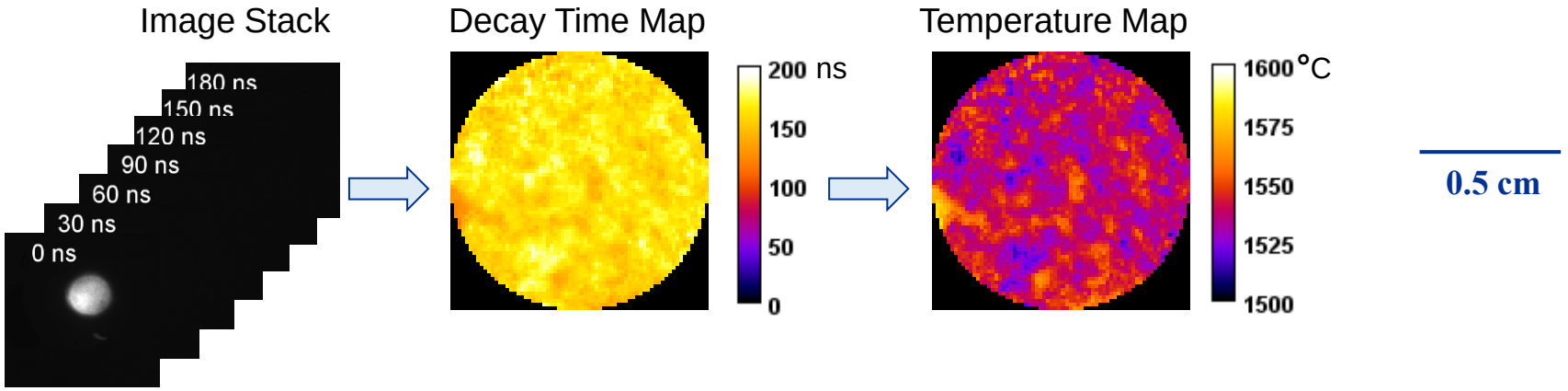


*Image processing developed by Adam Wroblewski at NASA GRC.

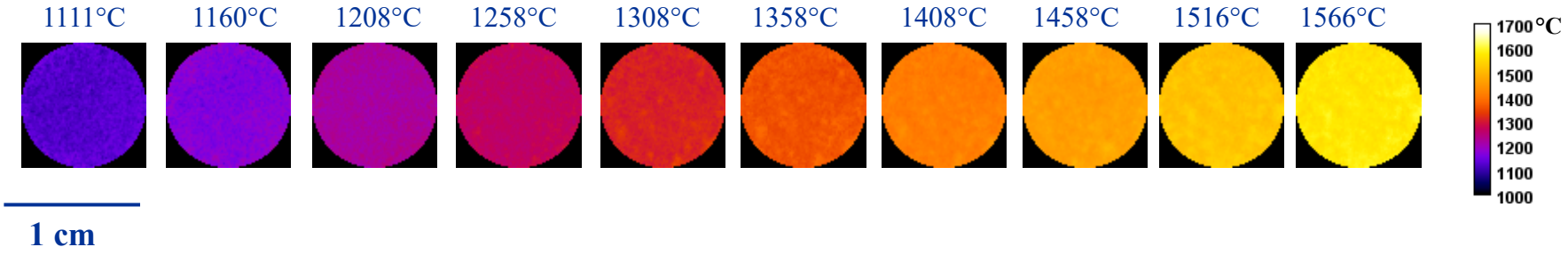
- Step 3: Use furnace calibration data to convert decay time map to temperature map.

$$\tau = [W_{10}(1 - e^{-\frac{\Delta E}{p_{high} kT}})^{-p_{high}} + W_{20}(1 - e^{-\frac{\Delta E}{p_{low} kT}})^{-p_{low}}]^{-1}$$

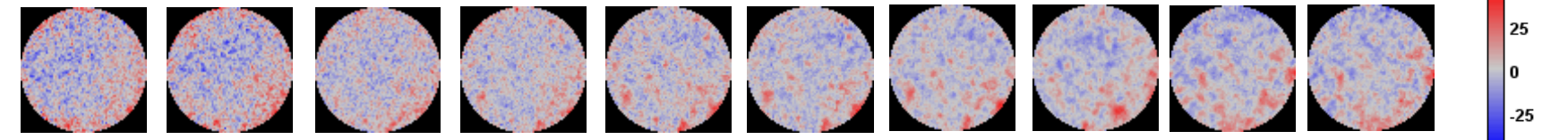
Dual effective phonon energy model

High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%) Luminescence Lifetime Temperature Maps

Temperature Maps



T – T_{mean} (shows deviations from mean)

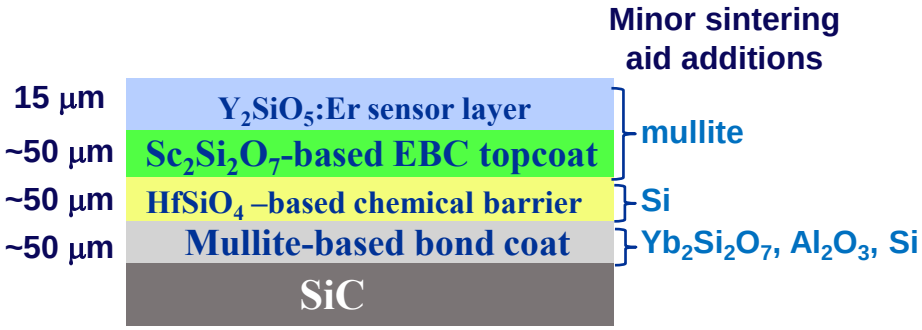


σ_T	11.4 °C	11.7 °C	9.0 °C	8.2 °C	8.6 °C	8.2 °C	7.8 °C	7.8 °C	8.9 °C	8.7 °C

⇩

0.5% relative temperature precision

Sensor Layer/EBC Architecture

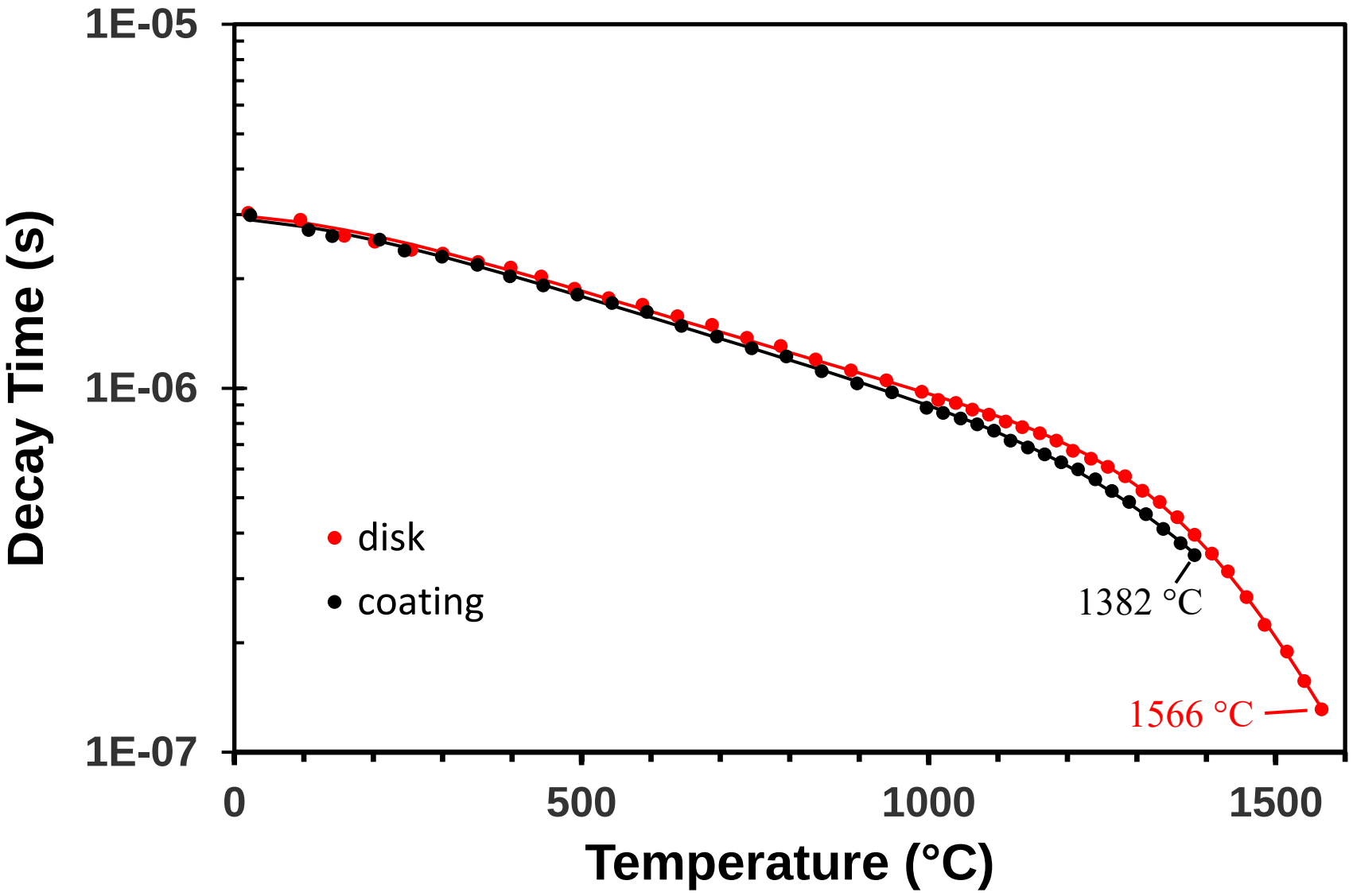


- Sensor coating + layered EBC deposited using slurry process* via spin coating.
  - Y_2SiO_5:Er selected for sensor layer instead of $Y_2Si_2O_7$:Er for stability because surface $Y_2Si_2O_7$ can convert to Y_2SiO_5.
  - Y_2SiO_5:Er sensor layer temperature limit reduced to < 1400 °C due to expected low melting temperature eutectic formed via sintering aid interaction.
  - Future transition to Sc_2SiO_5:Er sensor layer will increase temperature limit due to higher melting temperature eutectic.
- Verify temperature mapping performance with 11x reduced emission intensity from 15 μm thick Y_2SiO_5:Er sensor layer compared to 2 mm thick standalone disk.

*K.N. Lee et al., J. Eur. Ceram. Soc., 41 (2021) 1639-1653.

Y_2SiO_5:Er(0.8%) Luminescence Lifetime Measurements

Standalone Disk vs. Coating



High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps

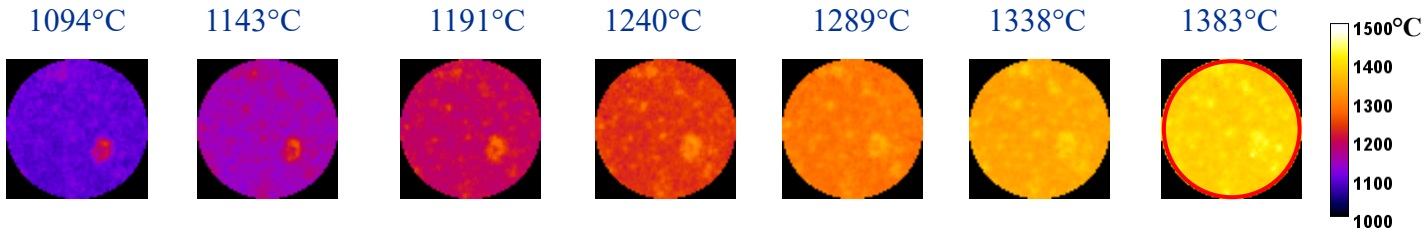
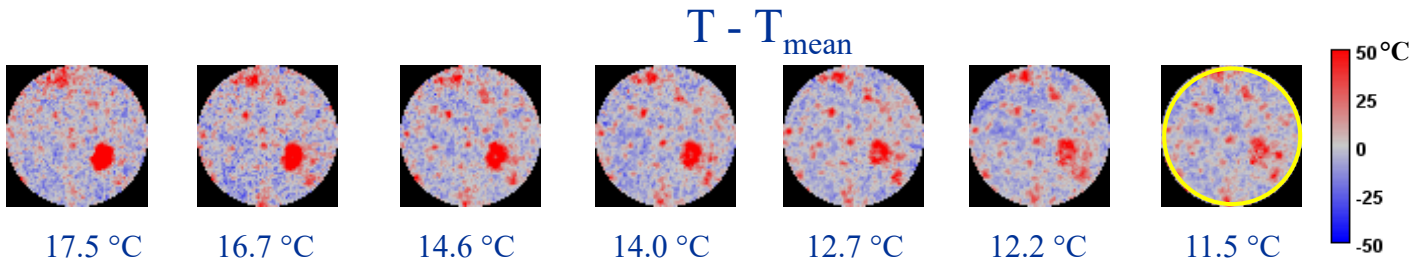


Image stack: 50 ns frame exposures

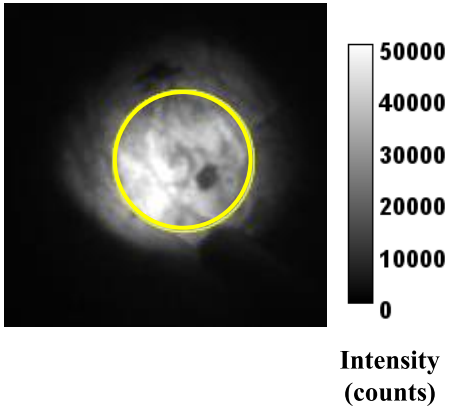


1 cm

⇩

0.7% relative temperature precision

1383 °C 50 ns exposure first frame in stack

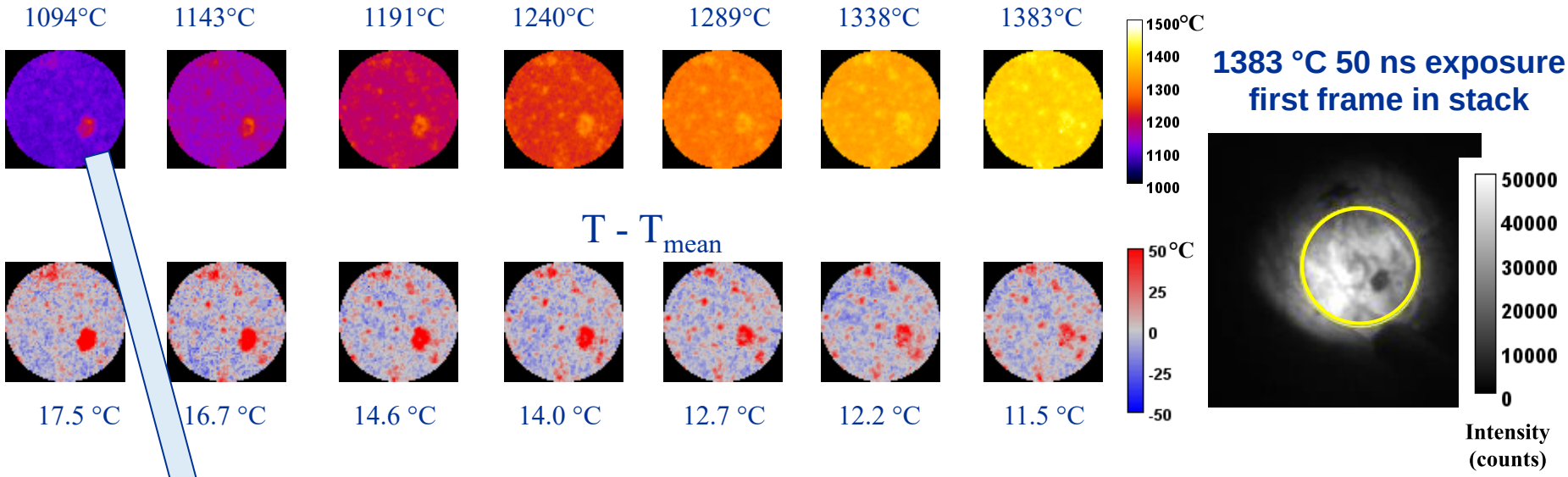


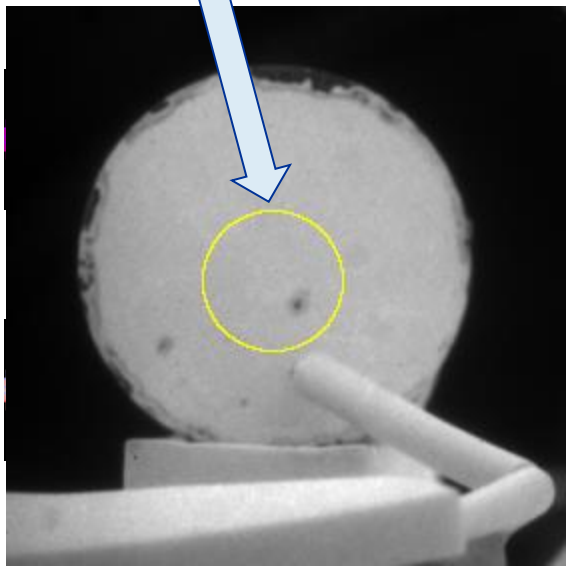
Excellent background suppression

Noisy in tails of excitation beam: exclude tails from analysis area.

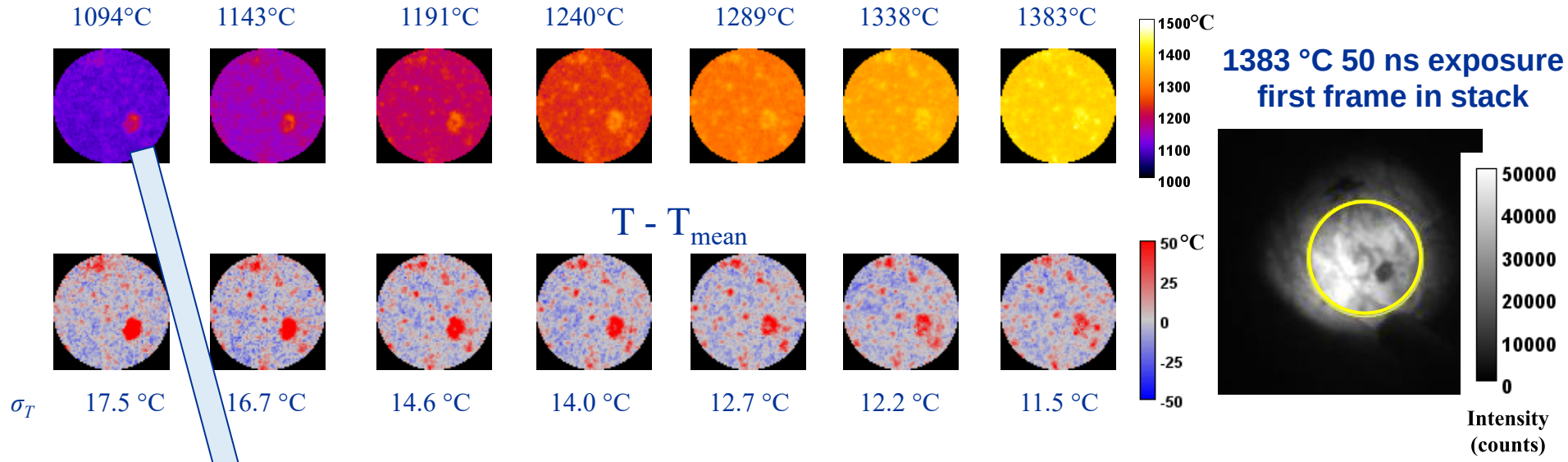
Prior to background subtraction!

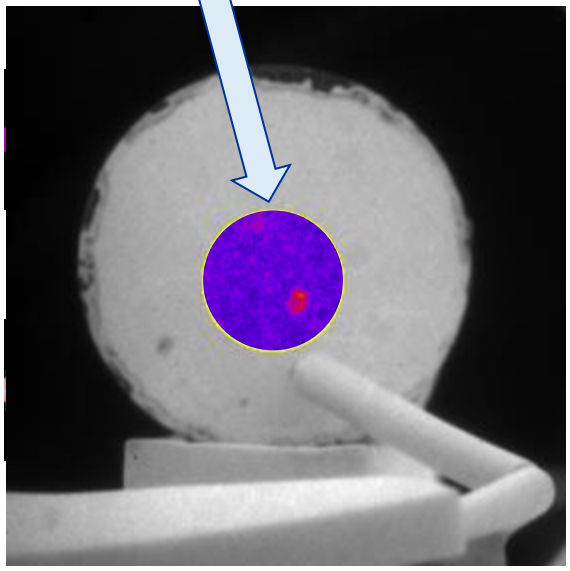
High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps





High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps





False "hot" spot due to coating defect

High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps

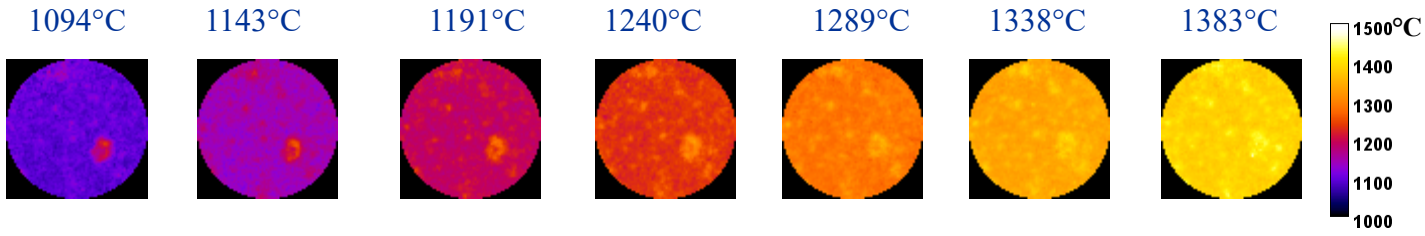
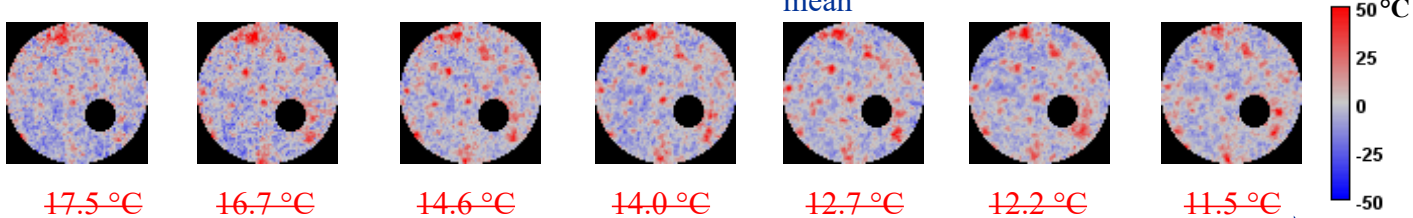


Image stack:
50 ns frame
exposures

$T - T_{mean}$



1 cm

σ_T

~~17.5 °C~~	~~16.7 °C~~	~~14.6 °C~~	~~14.0 °C~~	~~12.7 °C~~	~~12.2 °C~~	~~11.5 °C~~
10.5 °C	12.5 °C	11.3 °C	11.3 °C	11.1 °C	10.9 °C	10.6 °C

⇨ 0.7 → 0.6% relative temperature precision

σ_T : large decrease

σ_T : small decrease

High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps

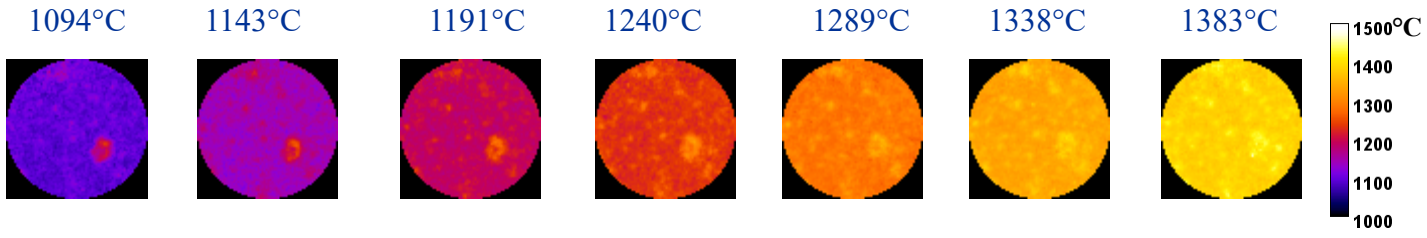
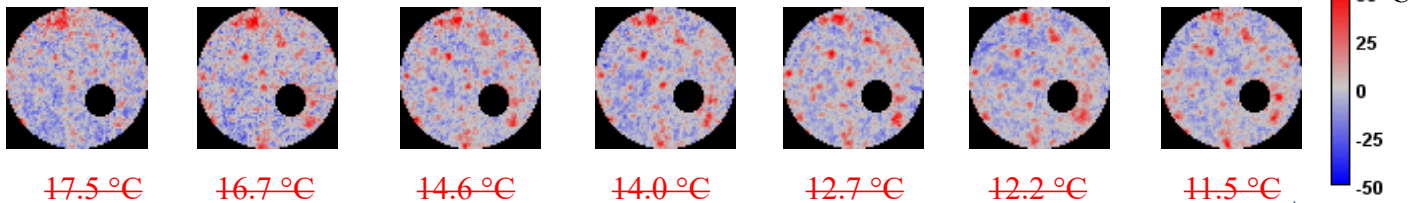


Image stack:
50 ns frame
exposures

$T - T_{mean}$



1 cm

σ_T

~~17.5 °C~~	~~16.7 °C~~	~~14.6 °C~~	~~14.0 °C~~	~~12.7 °C~~	~~12.2 °C~~	~~11.5 °C~~
10.5 °C	12.5 °C	11.3 °C	11.3 °C	11.1 °C	10.9 °C	10.6 °C

⇨ ~~0.7~~ → 0.6% relative temperature precision

Disk

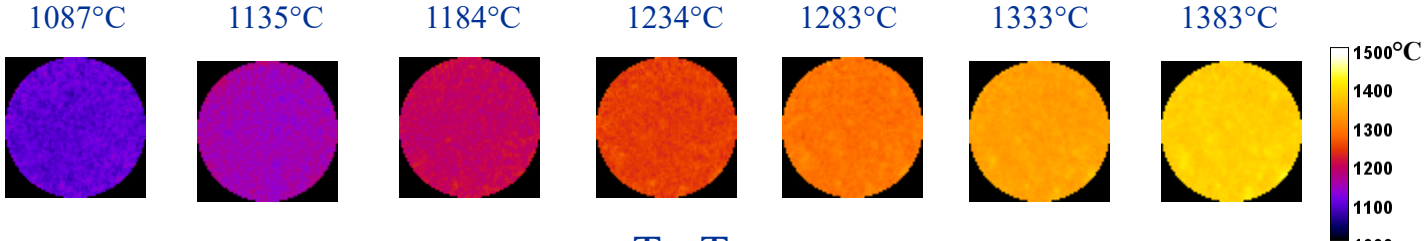
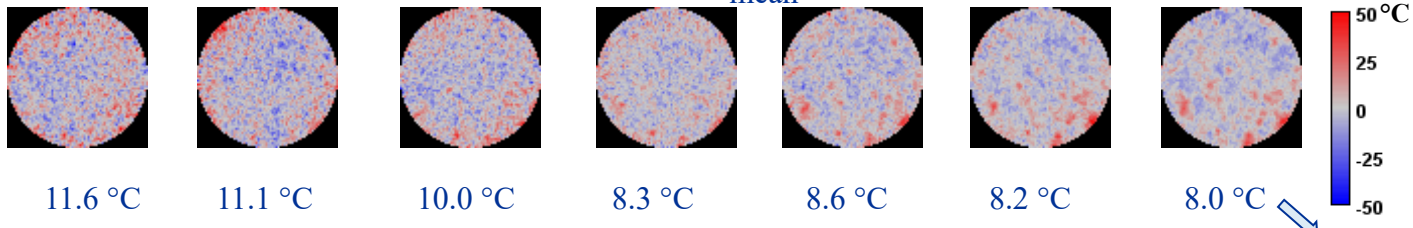


Image stack:
15 ns frame
exposures

$T - T_{mean}$



σ_T	11.6 °C	11.1 °C	10.0 °C	8.3 °C	8.6 °C	8.2 °C	8.0 °C
$\sigma_{\overline{T}}$	0.19 °C	0.18 °C	0.16 °C	0.13 °C	0.14°C	0.13 °C	0.13 °C

⇩ 0.5% relative temperature precision

High Temperature Furnace Calibrations
Y_2SiO_5:Er(0.8%)/EBC Luminescence Lifetime Temperature Maps

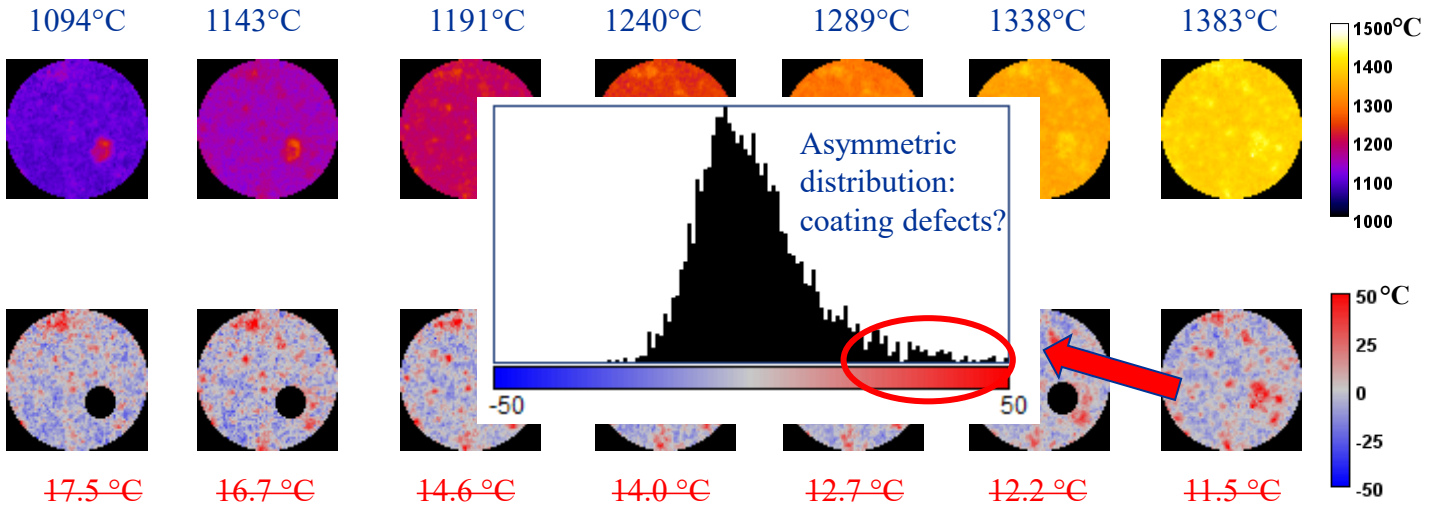


Image stack: 50 ns frame exposures

1 cm

σ_T ~~17.5 °C~~ 10.5 °C | ~~16.7 °C~~ 12.5 °C | ~~14.6 °C~~ 11.3 °C | ~~14.0 °C~~ 11.3 °C | ~~12.7 °C~~ 11.1 °C | ~~12.2 °C~~ 10.9 °C | ~~11.5 °C~~ 10.6 °C ⇨ 0.6% relative temperature precision

Disk

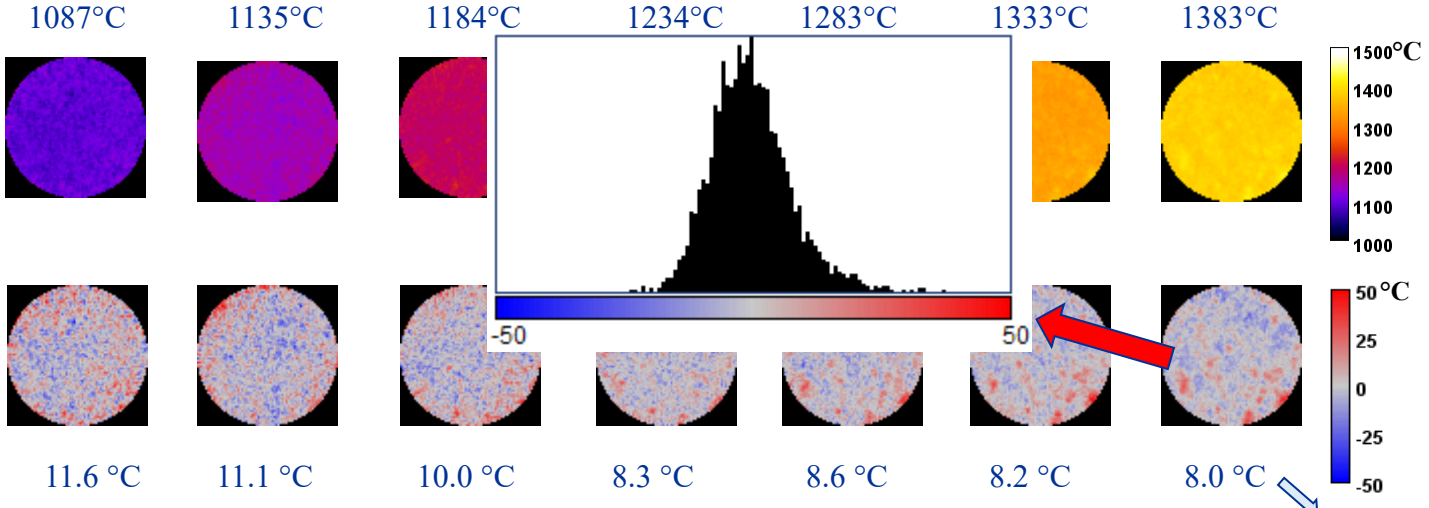


Image stack: 15 ns frame exposures

σ_T 11.6 °C | 11.1 °C | 10.0 °C | 8.3 °C | 8.6 °C | 8.2 °C | 8.0 °C

$\sigma_{\overline{T}}$ 0.19 °C | 0.18 °C | 0.16 °C | 0.13 °C | 0.14°C | 0.13 °C | 0.13 °C ⇨ 0.5% relative temperature precision

Conclusions

- Y_2SiO_5:Er shows temperature mapping potential for EBC-relevant temperatures (1300-1500 °C).
  - Stand-alone Y_2SiO_5:Er shows temperature mapping capability to at least 1566 °C.
    - Significant advance in extending phosphor thermometry temperature mapping to higher temperatures.
  - Excellent suppression of intense thermal radiation background.
  - 15 µm thick Y_2SiO_5:Er layer on $Sc_2Si_2O_7$ based EBC topcoat shows temperature mapping capability to at least 1383 °C.
    - Remains adherent.
    - No spectral evidence of chemical degradation observed but expected at higher temperatures.
- Next Steps
  - Y_2SiO_5:Er → Sc_2SiO_5:Er temperature sensing layer
    - Better compatibility with $Sc_2Si_2O_7$ EBC topcoat, extending mapping capability to higher temperature limit.
    - May reduce/eliminate false “hot” spots
  - Implement temperature mapping to evaluate cooling at EBC surface.

Funding from NASA Transformative Tools & Technologies (TTT) Project.